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A sustainable shipbreaking approach for cleaner environment and better wellbeing

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Abstract

Shipbreaking has great economic benefits but generates substantial hazardous materials as wastes to the surrounding environment of shipbreaking yards. Currently, a number of methods are exercised all over the world for breaking ships. However, 'beaching method' is of most concerns due to its nature of activities. A computer simulation has been carried out and the results reveal that the toxic wastes which, without proper management and treatment, accumulate on the yard ground and gradually diffuses into soil. Thus, leach to sea-water, contaminate and degrade water quality, create a declining trend of biotic structure and eventually affect the ecological systems resulting in sudden or gradual disappearance of mangroves and vegetation. Computer simulation results also confirm that if shipbreaking activities are performed on a bed that is constructed using pebbles of various sizes in such a way that the pebble size gradually increases and the bed permeability gradually decreases across the depth starting from the top surface of the bed, the concentration of hazardous materials could be restricted and catastrophic environmental damages could be avoided. The proposed shipbreaking approach is thought to be sustainable as it uses naturally found construction materials which could be reused for other purposes and offers cleaner, environmentally sound production process of raw materials without incurring significant implementation costs.

Keywords: ship recycling, shipbreaking, hazardous materials, diffusion, contamination.

1. Introduction

Shipbreaking is the fundamental and the main activity for ship recycling and refers to ship dismantling activities. Every year, approximately 5.8 million tonnes of steel materials are recycled worldwide from shipbreaking. Around 82 countries worldwide are involved in steel shipbreaking/recycling activities but the shipbreaking industries located in Bangladesh, India, Pakistan, China and Turkey altogether consistently recycle 97% to 98% of total tonnage recycled in the world (Kurt *et al.*, 2017). As high as 500,000 people in Bangladesh are directly and indirectly dependent on shipbreaking activities (Sarraf *et al.*, Dec 2010). Breaking/recycling of composites hull has not been started in the above mentioned countries yet. However, the rapid growth in the demand of composites hull will soon impose further threats to the leading shipbreaking countries. The toxic wastes from shipbreaking activities initially accumulate on soil but gradually reach to sea-water causing contamination and degradation of water quality as well as gradual disappearance of mangroves and vegetation. Shipbreaking activities not only damages the ecological systems but also creates health and mental problems for the workers due to poor sanitation facilities in shipbreaking yards (Devault, Beilvert & Winterton, 2017), continuous exposure to heat, dust, toxic chemicals, polluted smokes etc. The real scenarios in a shipbreaking yard located in one of the developing countries mentioned above is shown in Figure 1. It is a challenge for all authorities to implement tougher environmental laws in the shipbreaking yards located in developing countries where environmental laws are relaxed. While shipbreaking workers' health and wellbeing could be improved in those countries by supplying protective clothing and safety equipment as well as ensuring sufficient human rights, the implementation of protective measures to eliminate the chances of mixing hazardous materials with soil in shipbreaking yards is a real challenge due to additional financial costs. The shipbreaking industries, currently using beaching method, are desperately looking for affordable, improved, sustainable and cleaner production process due to tighter international regulations imposed upon them. Hence, this interdisciplinary collaborative research work has been conducted to develop a sustainable and environmentally friendly shipbreaking approach through effective control of mixing hazardous materials with soil in shipbreaking yards. It is anticipated that the proposed approach will not only be simpler to apply but also be cost effective. Therefore, the research results presented in this article would be advanced guidelines for the shipbreaking industries to achieve cleaner production of raw materials in environmentally friendly way resulting enhanced social welfare and blue economy..

Figure 1: Image depicting shipbreaking workers' continuous exposures into hazardous environments.

2. The interdisciplinary challenges associated in controlling hazardous materials produced from current shipbreaking activities

Steel is considered as the main construction material for ships. Most modern ships and other marine vessels are generally made of steel. A general cargo ship of deadweight (i.e. payload capacity) between 5000 and 15000 would normally have its lightship weight (i.e. a ship's own weight) between 35% and 20% of its total weight. If such cargo ship is scrapped or recycled, 55% to 64% of its lightship weight would generate steel, 19% to 33% of its lightship weight would provide outfitting and 11% to 22% of its lightship weight would be of machineries (Papanikolaou, 2014). In terms of steel contents, bulk carriers and tankers both are more demanding. This is because, 68-85%, 6-17% and 8-16% of a bulk carrier's lightship weight belongs to steel, outfitting and machineries respectively whereas these figures are 73-88%, 5-13% and 9-16% respectively for a tanker (Papanikolaou, 2014). Obviously, the percentage of steel content significantly depends on the size and the deadweight capacity of a vessel. Other than those two types of vessels, steel weight to lightship weight ratio would normally be around 50%. A large portion of the total steel recovered from shipbreaking is normally used by local steel mills and re-rolling mills as a raw material. Rest of the steel materials is either reused by the local shipyards for further shipbuilding, repairing and retrofitting purposes or processed for exporting. The countries in the CIS region, Asia, Europe and America altogether require the steel manufacturers worldwide to fulfil 75% of world's total steel demand (Mabashi & Mercier, 2019). The price and the supply of raw steel material as well as the steel products depend largely on the shipbreaking activities and have linear relationships. Previously, a report by Mabashi & Mercier (2019) had indicated that countries like India, the U.S., China, EU and Japan had reduced their steel exports in first 10 months of 2018 by 29.3%, 13.4%, 9.3%, 6.4% and 3.1% respectively. The prices of steel as raw material were increased in the first quarter of 2018 but reduced to a price similar to the previous years. The World Steel Association has made a press release (as a short range outlook) in April 2019 (WorldSteelAssociation, 2019) which indicates that the global demand for steel will increase to 1752 metric tonnes in 2020 and this is an increase of 1% compared to the current demand. It has also been anticipated in the same press release that the demand for steel will continue to grow but at a slower rate due to the world's current unfavourable economic environment. This situation has been caused due to uncertain trade policies and trade tensions between countries and regions as well as sluggish manufacturing performance in various parts of the world. However, the demand of steel is expected to grow in 2020 by 6.4% for developing countries in Asia excluding China (WorldSteelAssociation, 2019). In order to meet the forthcoming demands of steel, the shipbreaking activities in the developing countries from South-East Asia as well as other parts of the world will continue to grow. Hence, shipbreaking yards around the world are currently breaking ships at an exponential rate using various methods such as beaching method, alongside/pier breaking/wet berth method, slipway/slope/landing method, dry docking method, floating dock method.

Among the available shipbreaking methods, beaching method is of particular concern as it is considered as hazardous to both human health and the surrounding environment. This method uses natural sea beaches with high tidal zones and long mudflats. The ship, which is brought for breaking, is normally anchored just outside the beach. Cargos, ballasts and all other easily removable items are removed to make the ship as light as possible. During the time of high tides (especially in the spring season), the ship is driven with its full speed towards the beach until the ship is stranded in the mudflats (Figure 2). There are two usual practices that can be found in this condition. The shipbreakers either wait for the next tide to bring the ship as close as possible to the beach or start breaking. If they make the decision to go ahead with the first practice, the shipbreaking workers would walk through the mudflats during low tide to carry a chain or a strong rope towards the beached ship. They would attach one end of the chain or the rope to the bollard of the ship and the other end to a winch located in the beach. At the next high tide, the ship is towed by the winch towards the beach to make an easy access for breaking. In most usual cases, the ship reaches closer to the beach but still a bit far away from the actual beach. Hence, the shipbreaking activities generally take place in the mudflats. Once a ship is beached, it cannot be re-floated. Hence, the beaching method is considered as irreversible. Prior to shipbreaking for recovering steel; internal panels, furniture, sanitary items, electrical systems, electronics, decorative items etc. all are removed and sold to local markets for the buyers to re-use. The breaking activities start from the bow to get easy access to the rest of the hull. Shipbreaking workers normally use gas-cutting torches to cut the beached ship into pieces in the forms of steel plates and blocks which are then directly dropped to the mudflats and pulled to the beach using a chain and/or rope attached to the winch. In many occasions, the shipbreaking workers carry those steel blocks/plates on their shoulders towards the beach for further cutting into small pieces making those suitable for transporting to re-rolling steel mills. Not all of the steel materials recovered from shipbreaking would be transported to steel mills; some of the steel plates, frames, stiffeners, longitudinals could be reused by the shipbuilders for repairing or retrofitting of other ships. Sometimes, recovered steel materials are cut into square bars of few inches thickness to be used as reinforcements in concretes (Hossain, 2017).

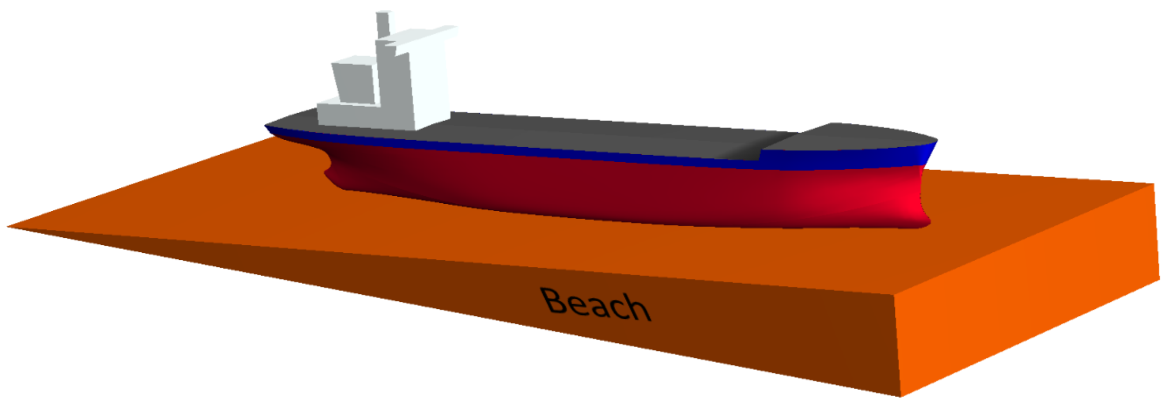

Figure 2: Ship beached for breaking in the mudflats of an intertidal zone.

The beaching method requires minimal infrastructural investments for the shipbreaking yards, thus, this method is considered as cheap, affordable, flexible and easily adaptable. This method is mostly applied by the shipbreaking industries located in Bangladesh, India and Pakistan (Litehauz, 2013). The main disadvantage of this method is that it generates hazardous wastes on the mudflats of a beach and it is impossible for the shipbreakers to perform cleaning exercises before the hazardous wastes been washed away by the tides towards the deep seas. As the beaching method of shipbreaking contaminates the mudflats and the surrounding environments, this method is not considered as environmentally sound.

Although a shipbreaking yard's main intention for breaking or recycling a ship using beaching method is to collect the ship's main structural material i.e. steel; the shipbreaking yard will also need to deal with a number of hazardous materials that are available on board of the ship waiting to be dismantled. While the selection of a suitable shipbreaking method is a shipbreaking yard's discretion, the identification and the management of hazardous materials both must be conducted by following the International Maritime Organization's (IMO) guidelines for safe and environmentally sound ship recycling. IMO's Marine Environment Protection Committee (MEPC) has published a Resolution (*Guidelines for the Development of the Inventory of Hazardous Materials - Appendix 5 - Example of the Development Process for Part I of the Inventory for Existing Ships:* , 2015) which provides a list of on-board hazardous materials and its probable locations as documented in Table 1 below.

Table 1: Type of hazardous materials on board of a ship and its probable locations within the ship as outlined in Resolution MEPC.269(68).

Hazardous Materials	Probable locations within a ship
Asbestos	Propeller shaft, diesel and gas turbine engines, exhaust gas economiser and heat exchanger, incinerator, pump, compressor, oil purifier, crane, pipe, duct, tanks, electric equipment, ceiling, floor and wall in accommodation area, fire door, fire proofing and fire-fighting equipment, inert gas system, air conditioning system, floor tiles, deck underlays, adhesives, fillers, thermal insulating materials etc. At the component level, asbestos is used for packing with flange, casing, casing door, manhole,

	hand hole, valve. It is also used as lagging material for fuel pipe, exhaust pipe, turbocharger, casing, steam line, drain line, valve etc. Also used as gasket material and brake lining.
Polychlorinated biphenyls (PCBs)	Transformer, condenser, fuel heater, electric cable, lubricating oil, heat oil, gaskets, hose and isolation mount made of rubber materials, plastic foam and thermal insulating materials, electric switch and voltage regulator, electromagnets, adhesives, tapes, oil based paint, pipe hangers, thermometers, sensors and indicators.
Ozone depleting substances (e.g. CFC, HCFC, HBFC)	Can be found as refrigerant in refrigerators and refrigerating machines, as a blowing agent in LNG carriers' insulation and as an extinguishing agent.
Organotin compounds (e.g. TBT, TPT, TBTO)	Can be present in anti-fouling paint.
Cadmium	Plating film and bearing
Mercury	Fluorescent light, mercury lamp, mercury and manganese cells, gyro-compass, thermometer, measurement tool, pressure sensors, light fittings and electrical switches.
Lead	Paints, corrosion resistant primer, preservative coating, soldering alloys, cable insulation, lead ballast, power generators (e.g. batteries).
Polybrominated biphenyls (PBBs), Polybrominated diphenyl ethers (PBDE) and chlorinated paraffin	Mainly found in non-flammable plastic components and products.
Radioactive materials	Ionization chamber, smoke detector, instruments, signs, high intensity discharge lamp, lighting rods, level gauges, dredger gauges, conveyor gauges, spinning pipe gauges.

In addition to the above hazardous materials, MEPC Resolution 269(68) has identified a number of potentially hazardous materials such as kerosene, lubricating oil, hydraulic oil, bunker fuel oil, sludge, grease, residues as oil and dry cargo, residues in fuel tanks and dry tanks, engine coolant additives, antifreeze fluids, water treatment agents, acids, alcohol, white and methylated spirits, paint and paint thinner, acetylene, propane, butane, perfluorocarbons and hydrofluorocarbons, methane, nitrous oxide, sulphur hexafluoride, bilge and ballast water, raw and treated sewage, chemical cleaners etc.

A number of published articles (Deshpande, Tilwankar & Asolekar, 2012; Du *et al.*, 2018; Glisson & Sink, 2006; Hiremath, Pandey & Asolekar, 2016; Hiremath, Tilwankar & Asolekar, 2015; Neser *et al.*, 2012) have discussed about the levels of contaminations of the hazardous materials (mentioned above) that are found at or around shipbreaking yards and indicated the likelihood effects of such contaminations. Lead (Pb) contamination can damage a person's neurological system, hearing system, kidney, heart, vision and blood vessels. Mercury (Hg) directly affects the human nerve systems. Although marine oils and fuels cause environmental damages through spillage, those also pose serious threats to human health if somehow consumed or inhaled. PCBs can damage liver, neurological and immune systems and cause cancer (Du *et al.*, 2018). The Health and Safety Commission of the United Kingdom has published a report on the effects of asbestos to human health when exposed to it. The report prepared by Doll & Peto (Doll & Peto, 1996) has identified that a person who is exposed to asbestos can develop lung cancer, mesothelioma (a type of cancer that surrounds an organ), gastro-intestinal cancer, laryngeal cancer etc. When a person is exposed to asbestos dusts, develops fibrosis of the lung better known as 'asbestosis'. The fibres of the asbestos dusts can remain in the lung for a long period of time before developing asbestosis. Hence, the control and the management of hazardous waste materials during shipbreaking is a real concern of all parties around the world. An example weight calculation of hazardous materials in IMO Resolution MEPC.269(68) demonstrates that each sheet of main engine packing or exhaust pipe packing contains around 250 grams of asbestos, a cylinder in a refrigeration plant may contain 20 kg of HCFC and a unit of battery may produce 6 kg of lead. This information provides a general idea about the quantity of some of the hazardous materials that could be available in a ship brought for breaking.

As per ship recycling guideline provided by the IMO, shipbreaking yards should complete a ship breaking/recycling plan prior to the arrival of the ship at the yard. This is to ensure that hazardous wastes that could be generated from shipbreaking activities are identified and handled properly before causing damages to the environment and posing threats to human health. If the IMO guidelines are followed properly, actually the owner of the ship sold for recycling/breaking would be primarily responsible to remove or minimise the amount of hazardous materials/substances available on board of the ship. However, the reality is too far from the moral obligations. In most cases, the ship owner takes advantages of the flaws in the laws and the regulations and passes all the accountabilities to the shipbreaking yards. On the other, shipbreaking yards might be pro-active to accept all the liabilities regarding identification, removal, disposal, transportation, management and recycling of hazardous materials available on board of the ship so that the overall purchase price becomes cheaper. In either case, there will be a number of interdisciplinary challenges which need to be mitigated prior to start shipbreaking activities. The most common interdisciplinary challenges associated in shipbreaking activities for managing hazardous materials are discussed below.

- **Missing or non-transparent "Green Passport"**

In the current shipbreaking practices worldwide, various skilled and honest surveyors are required to identify the hazardous materials present across a ship hull. Ideally, a ship sold for breaking/recycling should have come with a document known as "Green Passport". This document contains a list of hazardous materials transported by the ship in her lifetime as well as a list of potentially hazardous materials which had been used to construct and/or repair the vessel. It is the ship owner's responsibility to keep the green passport up-to-date throughout the operational life of the ship. The ship owner should, therefore, incorporate any information into the green passport regarding additions or removals of the hazardous materials during repair, modification or retrofitting of the ship. However, in most cases, this practice is not followed by the ship owner.

In the absence of accurate information, appropriate drawings and adequate instructions, it is hard for a surveyor to identify accurately all the hazardous materials on board with exact quantity and exact locations within a ship due to the nature of complexity in the design and construction of a ship. As a result, there is a significant chance that the authorities or agencies responsible for issuing various approvals for shipbreaking might issue no objection certificates while leaving some of the on board hazardous materials completely unidentified.

- **Non-idealised testing methods**

Various testing methods and practices are used worldwide to identify the type and the amount of hazardous and potentially hazardous materials on board of a ship that is waiting for breaking or recycling. The existence of asbestos can be tested using Phase Contrast Microscopy (PCM), Polarized Light Microscopy (PLM), Transmission electron Microscopy (TEM), Scanning Electron Microscopy (SEM), X-Ray Diffraction (XRD) etc (Du *et al.*, 2018). Each of these test methods follows different regulations and guidelines developed by various organisations and agencies from the United States of America, Japan and China. In addition, there are separate regulations and guidelines for detecting asbestos in different media such as air, water, soil or bulk materials. The detection of the existence of asbestos and its accurate amount may differ from one test method to the other. Hence, detection of asbestos is a challenge for shipbreaking yards in the absence of a single consolidated test method idealised by combining all available methods from all organisations and agencies around the world.

- **Lack of testing facilities**

Testing of various hazardous materials require skilled technicians, expensive equipment, sophisticated software and high standard laboratory facilities. The shipbreaking yards engaged in breaking majority of world's fleet are located in lower-middle-income countries. It is an expensive practice for the shipbreaking yards from this region to have their own laboratories and testing facilities. They mostly rely on central facilities provided and managed by the local/central government. However, certain types of hazardous materials may not be possible to test in those existing facilities. Du et al (2018) has reported that the detection of polychlorinated biphenyls (PCB) is normally carried out in developed countries like United States of America, Germany and Japan. China has also set up its own PCB detection and handling institution. Thus, detection and disposal of PCBs both are significantly challenging tasks for shipbreaking yards.

- **Lack of hazardous waste management facilities**

Likewise the detection process, disposal and management of hazardous materials are also expensive exercises. Careful planning, continuous maintenance and significant investment costs are the key factors in establishing effective hazardous waste management facilities. Hence, it may not be feasible for shipbreaking yards to have their own facilities. In the absence of own facilities, shipbreaking yards would mainly depend on private or government owned central facilities which may or may not exist at all or might be in plans for future development. The IMO and the Ministry of Industries of the People's Republic of Bangladesh have jointly conducted a project known as SENSREC Project-Bangladesh. The deliverable of the project's work package-2 (Asolekar, 2016) has identified that a common hazardous waste treatment, storage and disposal facility is required for effective management of hazardous materials and wastes from shipbreaking/recycling activities. Establishment of such facility at a confined and isolated location in Bangladesh would cost 11.5 million US dollar and this doesn't include land, utilities and management costs. Without having full and continuous access to such facilities, management of hazardous materials and wastes is a key challenge for shipbreaking yards.

- **Inconvenient transports and logistics**

In the case where the hazardous waste management facilities are located outside shipbreaking yards, appropriate means of storage and effective ways of transportation would be extremely challenging. IMO guidelines on ship recycling clearly state that the containers used for storing and transporting asbestos after removing from dismantled ship must be of sufficient strength so that uncontained release of asbestos fibres to the environment is avoided in the event of accidental damage or leakage to the containers during transportation. The same guidelines are also applicable to transport PCB materials when removed from ships.

- **Accidental spillage**

Shipbreaking yards are required to describe a plan and the procedure for protecting the environmental damage during their shipbreaking activities. IMO guidelines for safe and environmentally sound ship recycling has mentioned that shipbreaking yards should have containment and diversionary structures in place for preventing soil and water contaminations through accidental spillage of oil and other fluids. In addition, shipbreaking yards should have environmental protection measures during transportation and offloading of fuels. However, leaks can occur without prior notice as can be seen in Figure 3 which depicts that oil residues from dismantled ships stored in barrels (and already transported safely to the storage area) suddenly escaped to the store ground due to unnoticed leak development in one of the barrels. When spillage occurs over a solid ground, it is easier to use spill clean-up equipment. However, it is a significant challenge for shipbreaking yards to perform cleaning operation when spillage occurs over mudflats.

Figure 3: Escape of oil residue from a barrel kept in a storage area of a shipbreaking yard.

The interdisciplinary challenges that shipbreaking yards would normally face could be mitigated by adopting creative thinking, cohesive approach, careful planning, sustainable acts and efficient management practices for all parties involved. It is worth highlighting that the sooner the mitigation of interdisciplinary challenges would be, the quicker the implementation of the IMO's goal of safe and environmentally friendly shipbreaking or ship recycling practices worldwide would be. However, an overall social awareness is the key to adapt and implement a sustainable shipbreaking process and this key can be achieved easily when people have better understanding on the way the hazardous materials generated from shipbreaking activities diffuse into the surrounding environment and affect the human health.

3. The diffusion behaviour of hazardous materials from shipbreaking activities into the surrounding environment

In order to understand the diffusion behaviour of hazardous materials generated from shipbreaking activities; it is important to be familiarised first with the location and the layout of a shipbreaking yard as well as their usual practices, issues, concerns and contributions. Thus, the shipbreaking activities in a typical yard in Bangladesh has been chosen as a case study.

Most of the shipbreaking yards in Bangladesh are established on government lands with leasehold arrangements. Several shipbreaking yards are also established on privately owned lands. Until 2009, none of the shipbreaking yards was operating with appropriate licences and/or with proper health and hazard management systems. Consequently, the local environmental activists filed a case in the Supreme Court of Bangladesh to stop their activities. The court had ordered to close down all the yards with a provision to re-open only after complying with the government regulations. The court had also ordered that a ship with hazardous materials on-board may not be imported in Bangladesh

(NGO Shipbreaking Platform, 2017). In response to the court order, the Government of the People's Republic of Bangladesh had adopted "The Ship Breaking and Recycling Rules" in 12th December 2011 for safe and environmentally sound recycling in Bangladesh (Bangladesh Ministry of Industries, 2011). As explained in the rule, the control and management process of hazardous wastes and materials for a ship planned for breaking should follow the guidelines outlined below in Figure 4.

Figure 4: The control and management process of hazardous wastes and materials for a ship planned for breaking in Bangladeshi Shipbreaking Zone (BSZ).

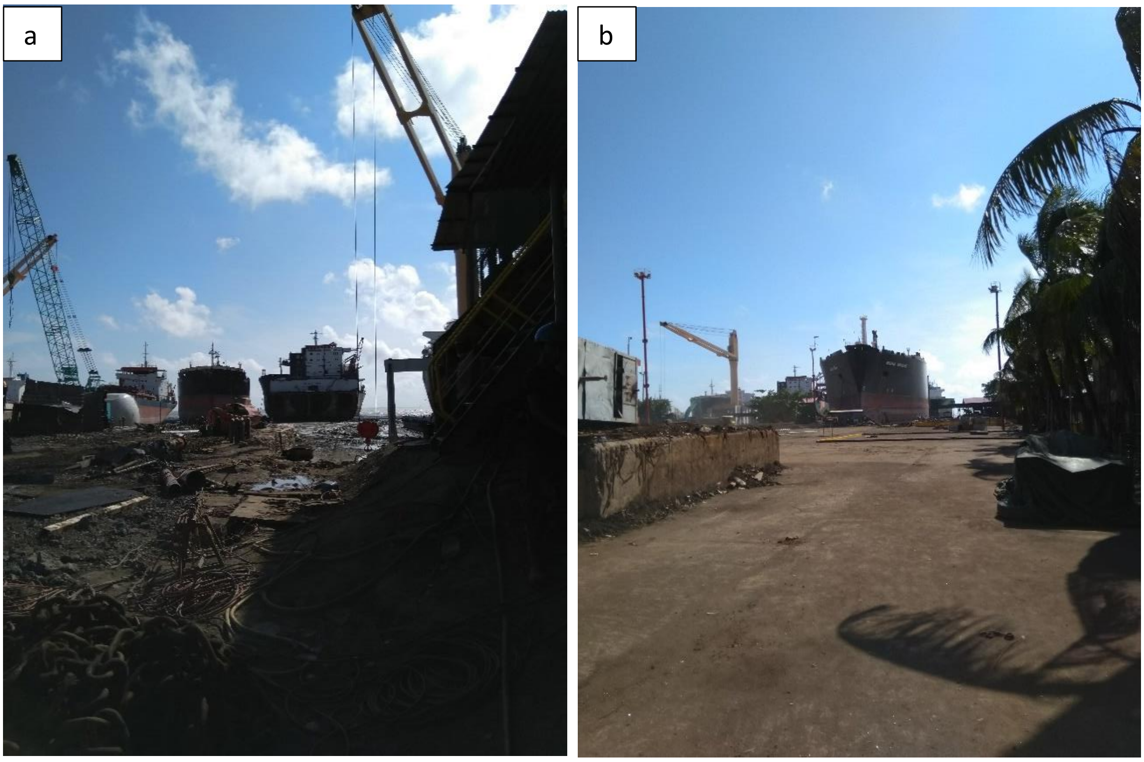

Figure 5: One of the shipbreaking yards in Chittagong, Bangladesh showing (a) the primary cutting zone and (b) the secondary cutting zone (i.e. materials processing zone).

A typical shipbreaking yard using beaching method is divided into two zones, one is the primary cutting zone and the other is called the secondary cutting zone. The primary zone is a part of the shore where ships are beached. This zone is used for first cutting of ships in big blocks. Onshore cranes are then utilised to bring those blocks onto the secondary zone. Further cutting operation is performed here to make small pieces of sheet materials. Both zones are shown in Figure 5 for comparison.

It is worth highlighting that the primary zone is entirely muddy zone and the secondary zone is made of hard/concrete surfaces. The entire surfaces of the muddy grounds in the primary cutting zone could easily be contaminated by the hazardous materials generated from the dismantled hull. On the other, the soils underneath the muddy surfaces in the primary cutting zone could also be contaminated due to diffusion and leaching of such hazardous materials as shown in the schematic diagram depicted in Figure 6. However, it is difficult to conduct physical experiments to identify the depth of the soil (underneath the primary cutting zone's muddy surface) that would be contaminated. This is because the morphology of the yard ground changes continuously. Therefore, a computer simulation is conducted to understand how far and how quickly the hazardous materials/substances can penetrate through the depth of the yard ground where beaching method is exercised.

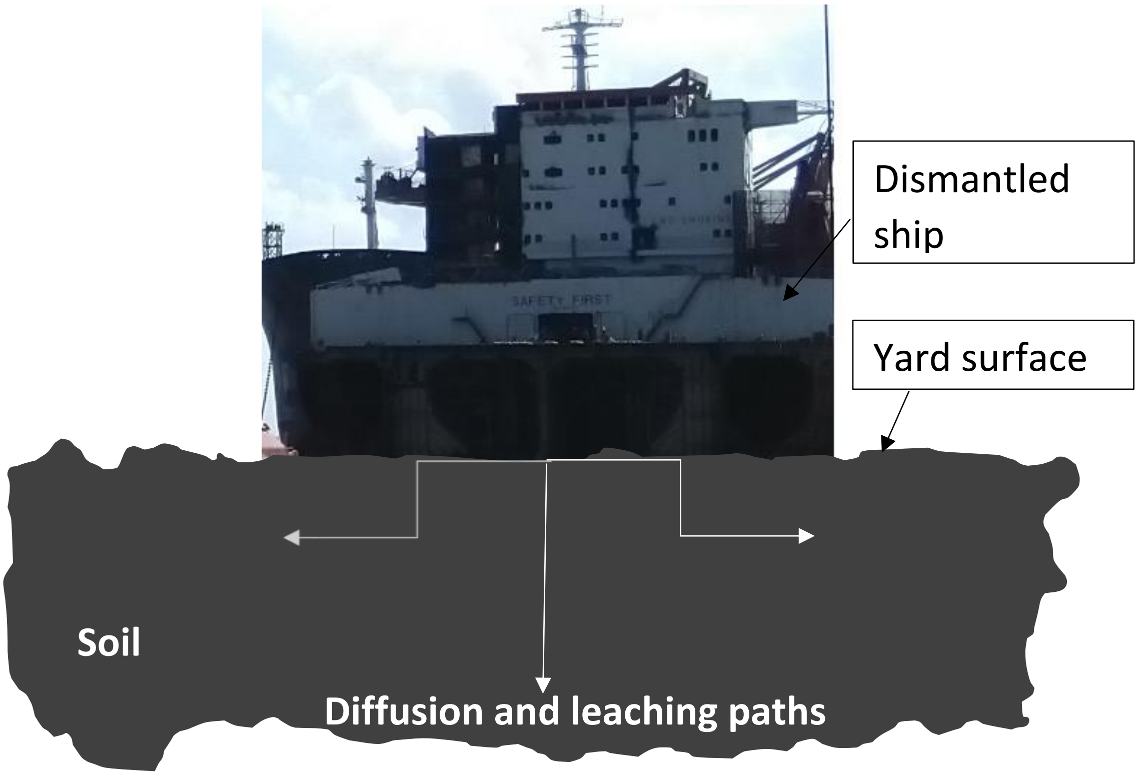

Figure 6: Schematic diagram depicting indicative diffusion and leaching paths of hazardous substances from shipbreaking.

3.1 Computer simulation methodology

Performing a computer simulation using a model of entire shipbreaking yard is very expensive in terms of computer hardware, software and execution time. In addition, current computer facilities are not fast enough to conduct a simulation for studying micrometre-level problems in kilometre-size domain. Hence, a portion of the shipbreaking yard highlighted in Figure 7(a) has been considered for performing simulation using a commercially available multiphysics simulation software COMSOL version 5.4. A three-dimensional computer model of radius and height both in one metre each has been developed as shown in Figure 7(b). The top surface of the model (indicated as “inlet”) is assumed as the shipbreaking yard’s exposed muddy surface where the primary cutting takes place. The bottom surface of the model designated as “outlet” represents the maximum depth of the ground. It is assumed that two types of hazardous materials resulting from shipbreaking activities will be deposited on the “inlet”. Since the inlet is at a muddy zone, the hazardous materials will be diluted in water and will form a hazardous material solution through reversible catalytic chemical reaction during diffusion into soil/sand. The reaction kinetics are considered as equimolecular in which the reaction rate is expressed in the following form (COMSOL, n.a.):

$$r = k^f C_{HazMat1} C_{HazMat2} - k^r C_{HazMatS}^2 \tag{1}$$

Where, k^f and k^r are the rate factors for forward and reverse reactions respectively, $C_{HazMat1}$, $C_{HazMat2}$ and $C_{HazMatS}$ are the concentrations of hazardous material 1, hazardous material 2 and the solution product of the hazardous materials respectively. COMSOL uses Arrhenius expression for the forward reaction constant and the equilibrium constant for the reverse reaction. It is worth mentioning that the reaction rate is assigned only on the top one-quarter depth of the model so that the diffusion paths for the hazardous materials and the hazardous materials’ solution can be of reaction rate independent across the remaining depth of the yard ground.

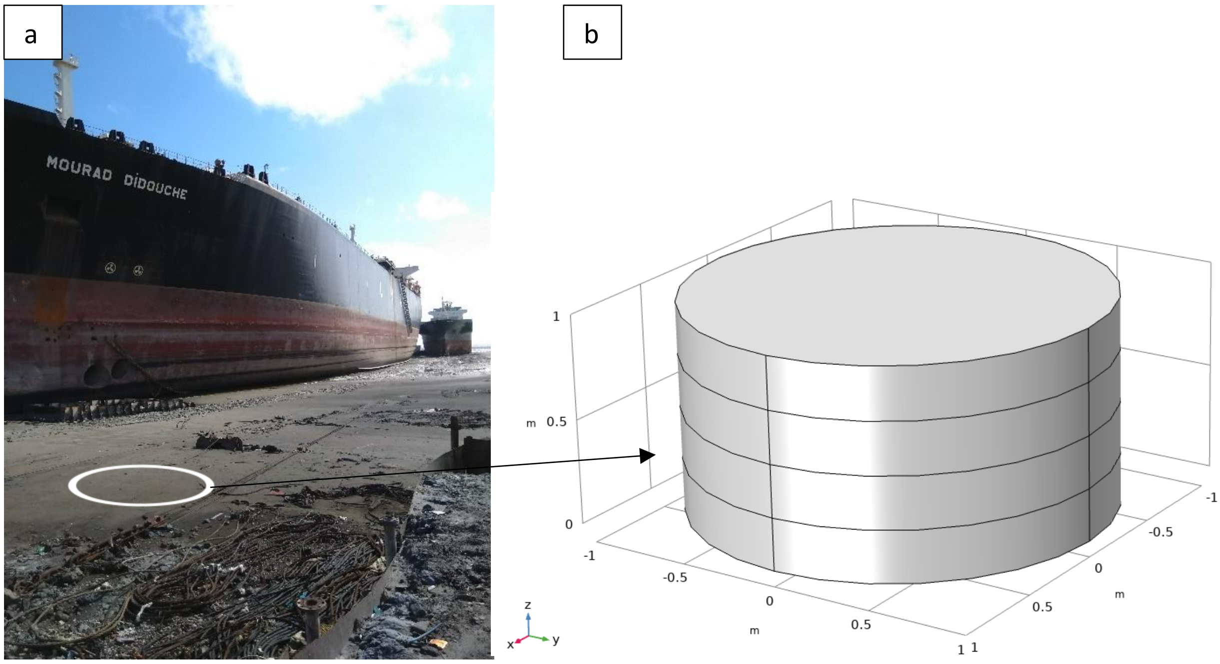

Figure 7: A typical sand/muddy surface of a primary cutting zone in a shipbreaking yard (a) and a three-dimensional model of the portion of the yard highlighted in white circle (b).

The computer simulation is performed with the assumption that the sand/soil particles are spherical in shape and will experience both reaction and diffusion. This assumption is incorporated into the simulation using the following equation suggested in COMSOL Application document (COMSOL, n.a.):

$$4\pi N\left(r^2 r_{pe}^2 \varepsilon_{pe} \frac{\partial c_{pe}}{\partial t} + \frac{\partial}{\partial r}\left(-r^2 D_{pe} \frac{\partial c_{pe}}{\partial r}\right) = r^2 r_{pe}^2 R_{pe}\right) \quad (2)$$

Where, N is the number of particles per unit volume, r is the non-dimensional radial coordinate from the centre to the surface of the particle, r_{pe} is the particle radius that can be changed without changing the geometry, ε_{pe} is the porosity of the particle, c_{pe} in mol/m^3 is the concentration of hazardous materials in the particle, D_{pe} in m^2/s is the diffusion coefficient of hazardous materials into the particle and R_{pe} in mol/m^3-s is the reaction source term for the particle.

The porosity of the yard ground (ε) is calculated based on the density of the yard ground (ρ_{yard}) and the density of the sand/soil particles (ρ_{pe}) using the expression shown below:

$$\varepsilon = 1 - \frac{\rho_{yard}}{\rho_{pe}} \qquad (3)$$

At the outer surface of each particle, a solid-fluid interface might be formed during the diffusion of hazardous materials in its solution form. Thus, the solution may create a resistance to mass transfer. This phenomena is also included into the simulation through the use of the following equation derived by COMSOL (COMSOL, n.a.):

$$N_{inward} = h_D\left(c - c_{pe}\right) \qquad (4)$$

Where, N_{inward} in mol/m^2-s is the molar flux from the solution into each particle, h_D is the film mass transfer coefficient and c in mol/m^3 is the concentration of the hazardous materials in the solution.

The diffusion phenomena is applied with a pressure differential between the top surface of the model (i.e. inlet) and the bottom surface of the model (i.e. outlet). The pressure drop across the height of the model is simulated using Darcy's Law.

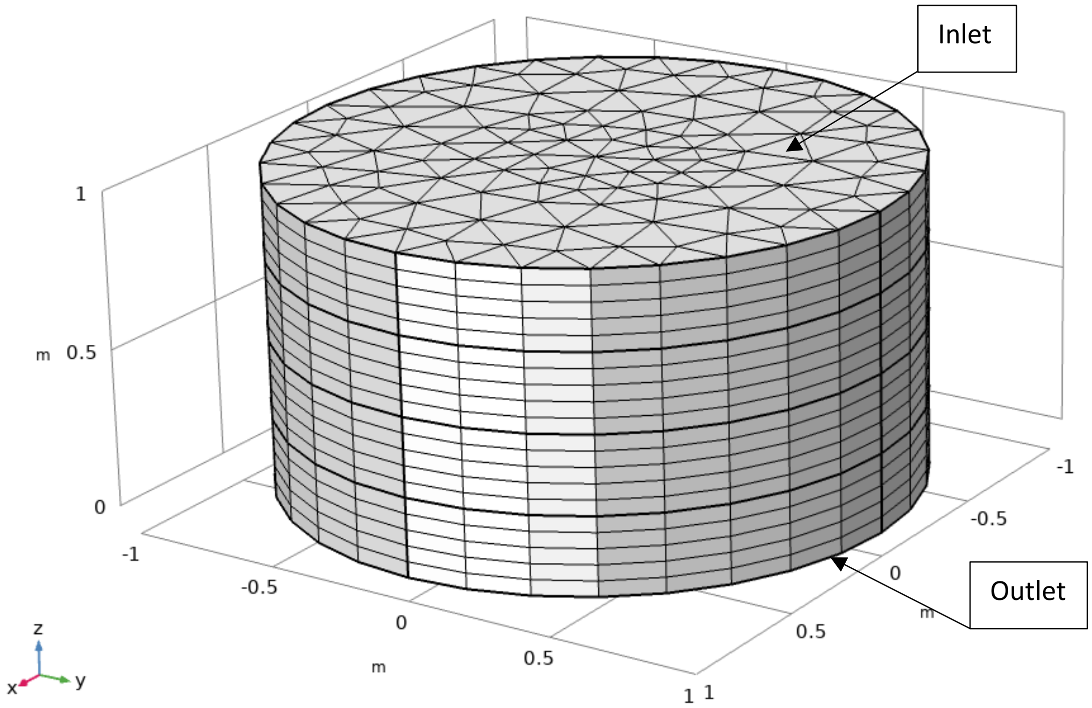

Figure 8: Mesh of the computer model representing a portion of the shipbreaking yard.

In order to perform the simulation by solving the above mentioned equations, the model is discretized into small elements as can be seen in Figure 8. The technique is better known as "mesh" or "meshing". A sizing option has been added into the meshing process to control the size and the number of elements. Firstly, the bottom surface of the model (indicated as outlet) has been meshed using "Free Triangular" element option then swept across the height to obtain the required mesh for the entire model. Usually the finer the mesh the better the solution quality. Finer mesh also helps a solver to achieve convergence with higher order of fidelity.

However, the finer the mesh, the slower the solution process is. To obtain a reliable solution outcome, the effect of mesh density i.e. mesh sensitivity has been tested with various number of elements (shown in Figure 9) and the results are presented in Table 2. It is worth mentioning that the mesh sensitivity study has been performed in the vertical direction (i.e. across the height) first and the transitions among the colour variations, which represent the concentration gradients, have been investigated. In order to ensure smooth transitions of the concentration levels of hazardous materials between the adjacent layers across the height, a biased meshing technique has been utilised to achieve denser meshes across the boundaries. The mesh analyses results confirm that the concentration levels of hazardous materials do not rely on mesh densities. The solution time for the model using 32GB RAM in a 64-bit core i5-7500T@2.7GHz CPU is 8min 45sec, 36min 14sec, 1h 55min 7sec and 5h 53min 38sec for extra coarser (640 elements), coarser (5440 elements), nominal (16640 elements) and finer (50400 elements) mesh qualities respectively. A nominal mesh quality would be appropriate to present the simulation results so that the model's morphological characteristics are not lost in the visual presentation of the results (Figure 10). However, a coarser mesh will be used in the parametric analyses as huge number of simulations will need to be performed for achieving an optimal value.

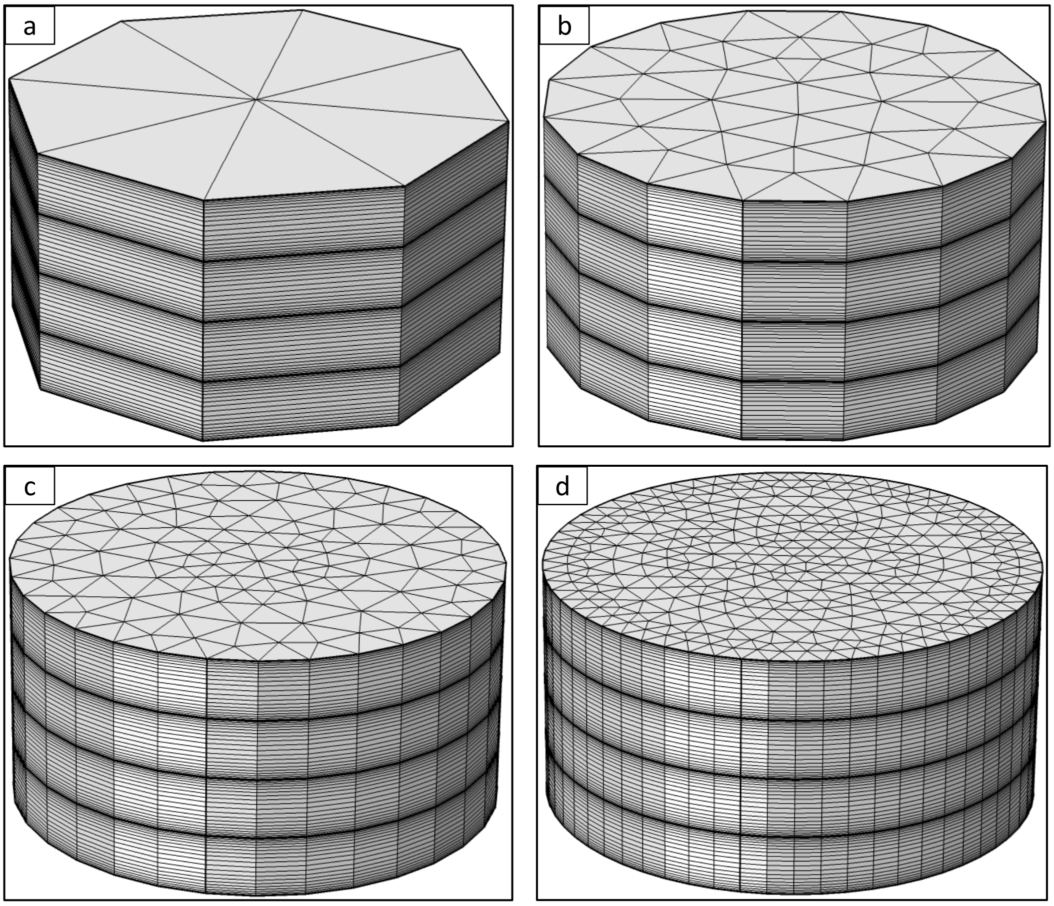

Figure 9: Mesh of the model used in computer simulation with (a) 640, (b) 5440, (c) 16640 and (d) 50400 elements.

Table 2: Concentration of hazardous material 1 at the centre of the model after 180 seconds.

Mesh quality	Number of elements	%change in concentration
Extra Coarser	640	0
Coarser	5440	0
Nominal	16640	0
Finer	50400	0

The computational simulation studies have been performed using the input parameters presented in Table 3. The input values are based on the data presented elsewhere (COMSOL, n.a.; Gawdzik & Zygadlo, 2010) and are used in the simulation as the nominal values.

Table 3: Input parameters used in the computer simulations.

Parameters	Value	Unit
Density of the yard ground	510.00	kg/m^3
Density of sand/soil particles in the yard ground	680.00	kg/m^3
Porosity of sand/soil particles in the yard ground	0.34	
Radius of sand/soil particles in the yard ground	5.00e-4	m
Diffusion coefficient of hazardous material 1 in particle	1.50e-9	m^2/s
Diffusion coefficient of hazardous material 2 in particle	2.00e-9	m^2/s
Diffusion coefficient of hazardous materials' solution in particle	1.00e-9	m^2/s
Permeability of the yard ground	1.88e-10	m^2
Initial concentration of hazardous material 1 at the yard surface of the primary cutting zone	1.00	mol/m^3
Initial concentration of hazardous material 2 at the yard surface of the primary cutting zone	1.00	mol/m^3
Initial concentration of hazardous materials' solution at the yard surface of the primary cutting zone	0.00	mol/m^3
Diffusion coefficient of hazardous material 1 in yard ground	1.00e-8	m^2/s
Diffusion coefficient of hazardous material 2 in yard ground	1.50e-8	m^2/s
Diffusion coefficient of hazardous materials' solution in yard ground	0.50e-8	m^2/s
Molar mass of hazardous material 1	1.8e-2	kg/mol
Molar mass of hazardous material 2	2.0e-2	kg/mol
Molar mass of hazardous materials' solution	1.9e-2	kg/mol
Molar mass of water on the surface of the yard ground	1.8e-2	kg/mol
Density of water on the surface of the yard ground	998.00	kg/m^3

In addition to the above parameters, the activation energy of the reaction is considered as 75,000 J/mol. It is also assumed that the nominal pressure on the surface of the yard ground is 1.0 atm, i.e. 101,325 Pa.

3.2 The diffusion behaviour of hazardous materials

A concentration gradient of hazardous material 1 across the depth of the yard ground at 1.0 atmospheric pressure is presented in Figure 10 at 180th second of the simulation. The hazardous materials are deposited on the top surface (inlet) of the shipbreaking yard's ground. During the diffusion process, chemical reaction takes place at a reaction rate calculated from equation 1. The hazardous materials start to deposit on the top of the yard surface and gradually diffuse into the ground, thus entire soil becomes contaminated. It is worth mentioning that the reaction rate is only assigned across the top quarter depth of the model, hence, the concentration level is varying for this part of the model. A smooth transition between the colours representing the concentration levels of hazardous materials ensures that the solution has reached required convergence criteria. The top surface of the yard ground has the highest concentration levels. This is because the hazardous materials were initially accumulated on this surface. As the time progresses, the hazardous materials slowly diffuse into the ground and create various layers of concentration levels. In other words, the hazardous materials generated from shipbreaking activities contaminate the soil of a yard's ground through gradual diffusion and leaching.

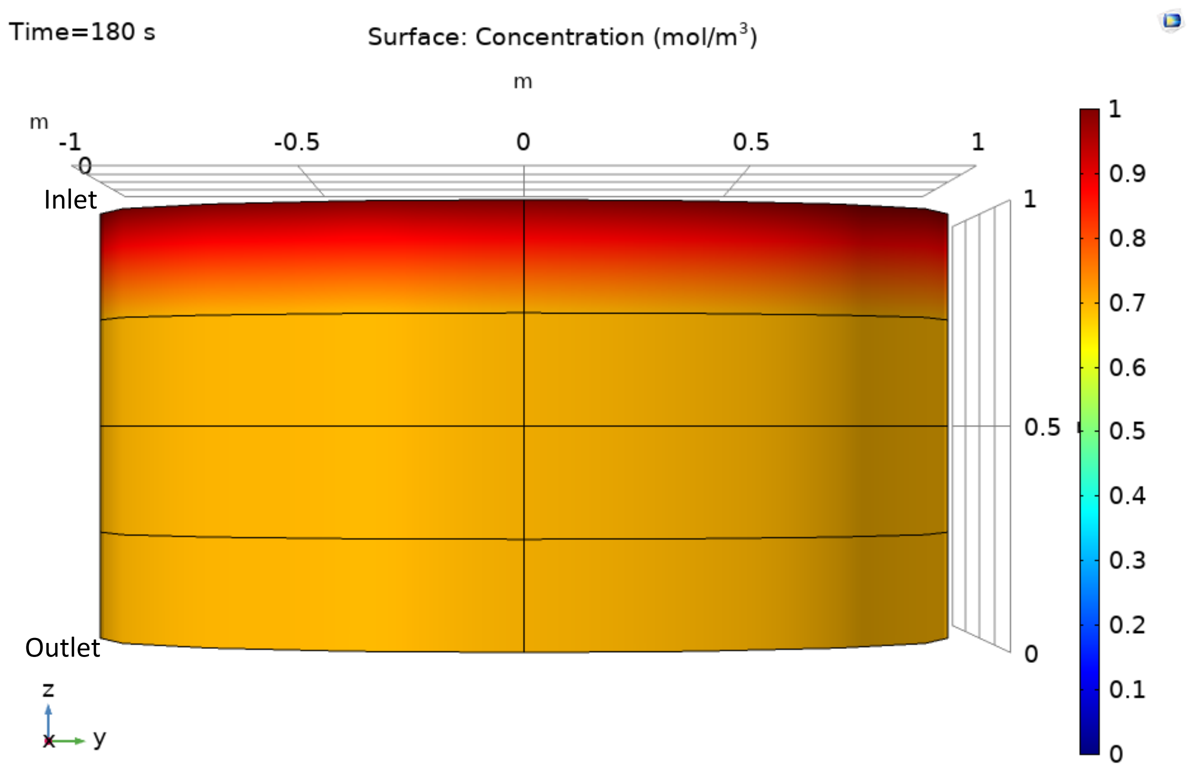

Figure 10: Concentration gradient of hazardous material 1 across the depth of the yard ground at 1.0 atmospheric pressure.

Figure 11 represents variations in the concentration levels of hazardous materials across the depth of the ground at 180th second of the simulation. In the plot, a height of 0 m means the maximum depth of the ground i.e. the outlet representing the base of the ground and a height of 1 m means the top surface of the yard ground i.e. the inlet. The figure reveals that both hazardous materials have similar concentration levels which vary significantly across the depth of the ground. Across the top quarter depth of the ground, the concentration levels of both the hazardous materials have been reduced gradually, however, these remained unchanged until towards the maximum depth of the ground.

The concentration level for the solution product of the hazardous materials is exactly opposite in the tendency which has been observed for each of the hazardous materials across the top quarter depth of the ground. It is interesting to note that while the concentration level of each of the hazardous materials is reducing across the top quarter depth of the ground, the concentration level for the solution is increasing. For most of the remaining depth of the ground, the hazardous materials' solution is simply transported with the same concentration level. This is because both hazardous materials took part in the chemical reaction when mixed up with water in the top quarter depth of the ground. Thus, the individual quantity of each of the hazardous materials is decreased in that region of the ground and this contributed to the increase in the amount of the solution product. Once the reaction zone is over, both the hazardous materials then simply diffuse into the ground and ultimately reach to the base. It is expected that a shipbreaking yard will experience standard atmospheric pressure (i.e. 1.0 atm) constantly, however, pressure differential may occur due to a yard's geographical locations and the so-called sea breeze effects. Therefore, it would be interesting to investigate the diffusion behaviours of hazardous materials if the shipbreaking yard experiences variations in atmospheric pressure. Figure 12 demonstrates that the concentration level is very much dependent on the atmospheric pressure on the top surface (as indicated in Figure 10) of the yard ground. When the atmospheric pressure is very negligible (e.g. 0.01 atm), it is very hard for the hazardous materials to diffuse into the yard ground and travel to a long distance. Hence, the hazardous materials remain concentrated near the top surface of the yard ground. This means that the top soil of the yard ground would only be contaminated. As the atmospheric pressure increases, the concentration levels of hazardous materials also increase across the depth of the ground. Since, shipbreaking yards are generally located near the sea (this assumption is also considered in the current simulation), it is appropriate to consider the standard atmospheric pressure environment (i.e. 1.0 atm) to study the diffusion behaviours of hazardous materials across a shipbreaking yard's ground. Hence, further investigations in this study are conducted for 1.0 atm.

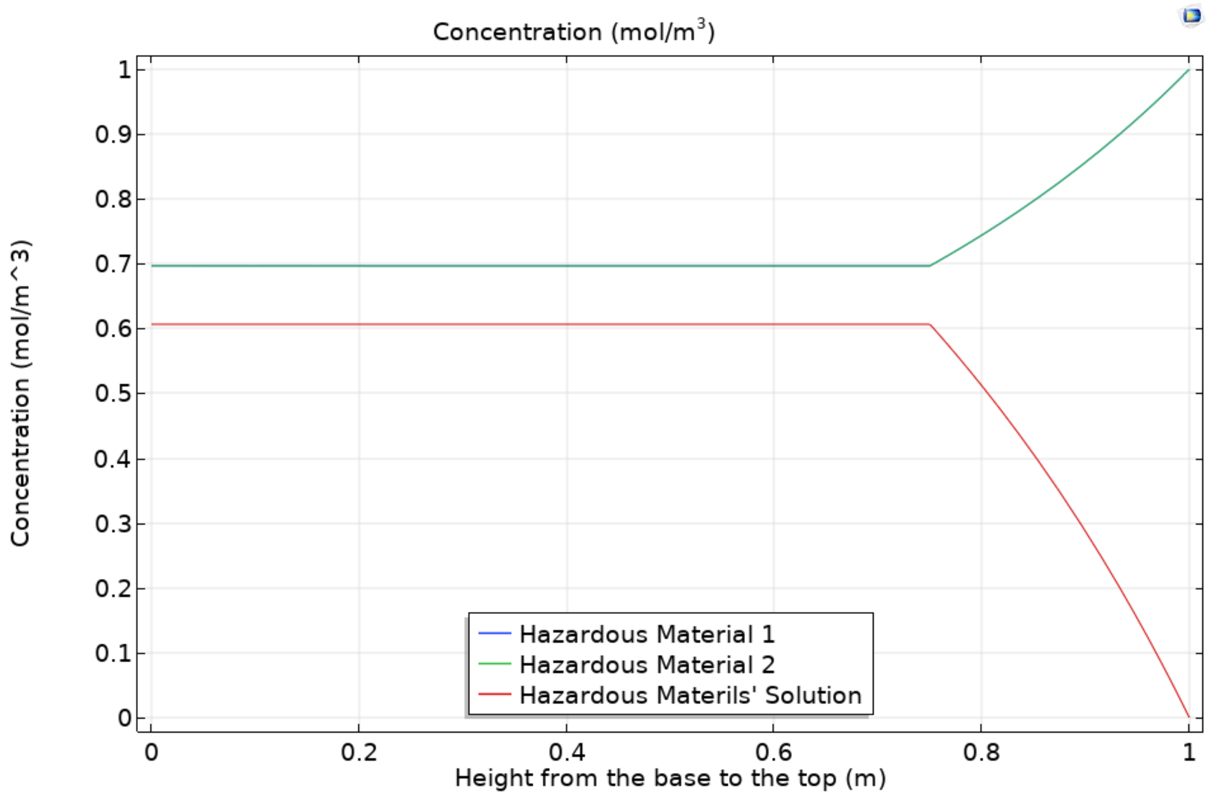

Figure 11: Plot of concentration of hazardous materials and the solution product across the depth of the yard ground at 1.0 atmospheric pressure.

It is worth mentioning that the simulation results presented in Figures 10-12 are based on the assumption that two types of hazardous materials resulting from shipbreaking activities deposit on the yard surface located in a muddy zone. The hazardous materials dilute in water available within the mud and form a hazardous materials' solution following an equimolecular reaction kinetics during diffusion in soil/sand. However, in the case where reaction doesn't take place at all, the hazardous materials should simply be transported by water through the porous media i.e. through the soil of the yard ground. Figure 13 depicts the concentration level of hazardous material 1 across the depth of the yard ground when no reaction takes place. It is evident that the hazardous material is mainly concentrated around the surface of the yard ground and slowly diffuses into the yard ground over time. Based on the input parameters supplied to the simulation, it only takes 110 seconds for the hazardous material 1 to diffuse into one meter depth of the yard ground. Similar tendency is also observed for the other type of hazardous material considered in the simulation.

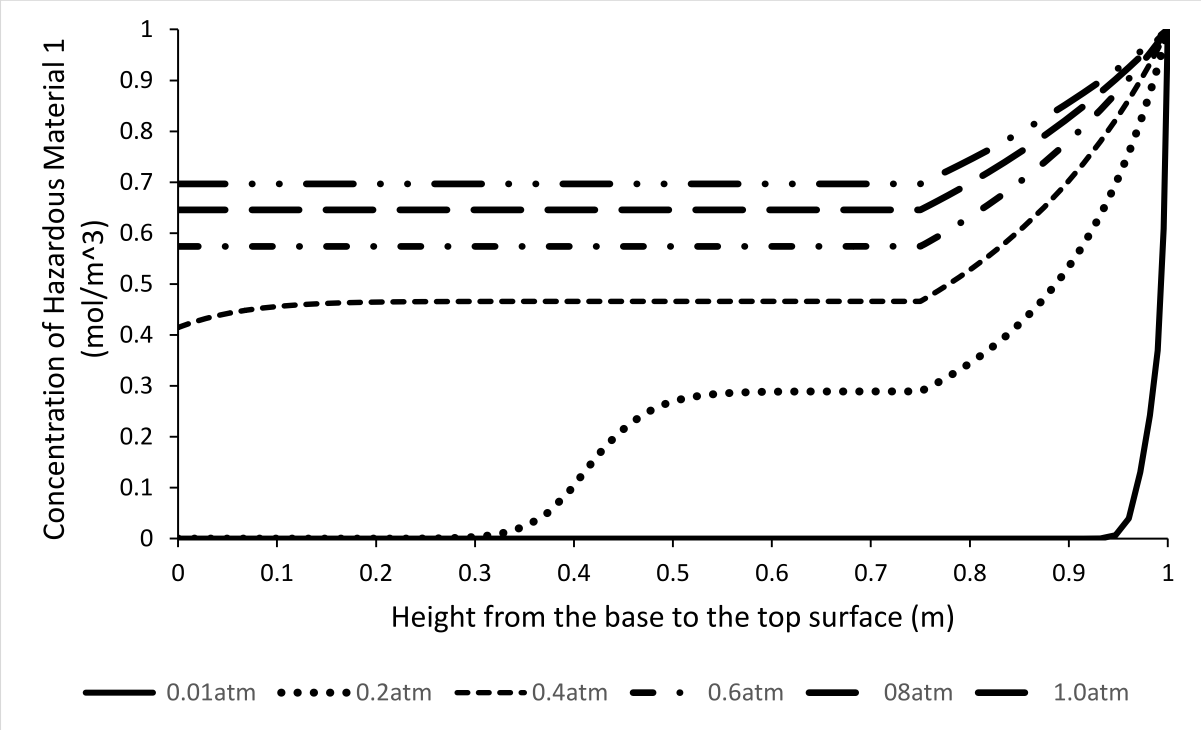

Figure 12: Concentration of hazardous material 1 at 180th sec with various atmospheric pressures.

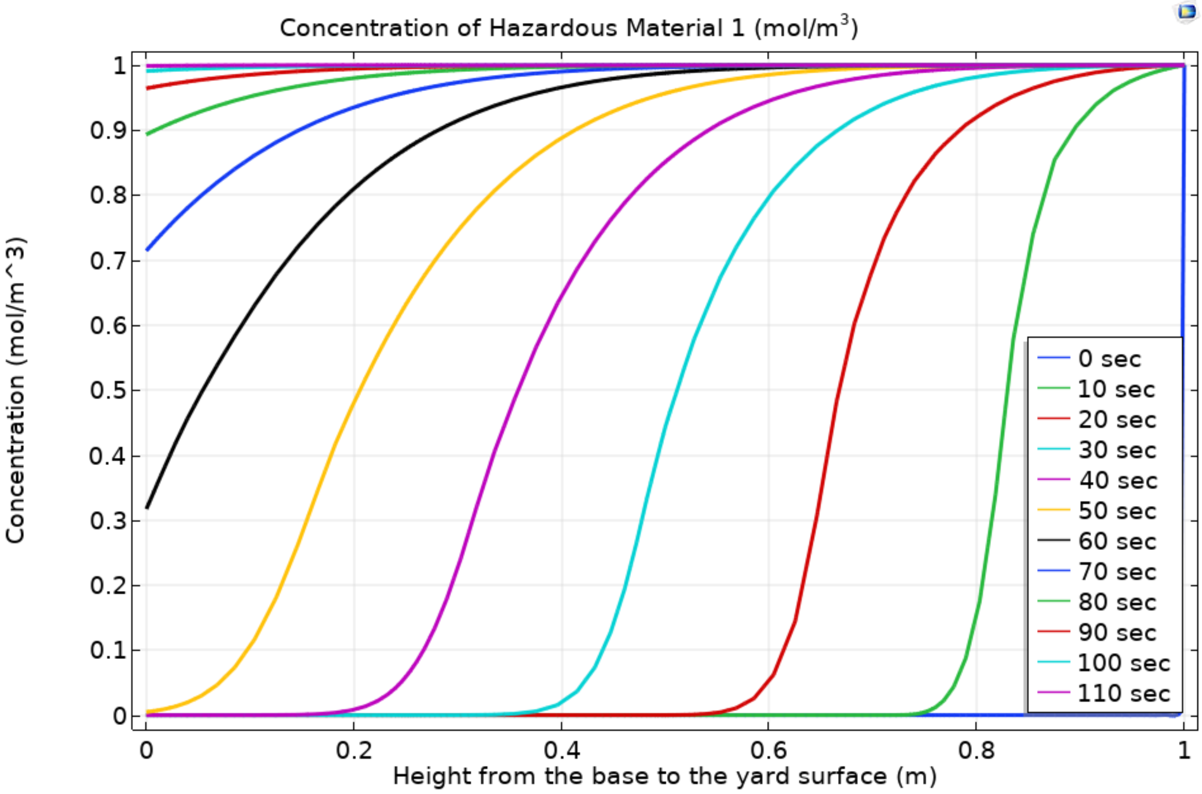

Figure 13: Concentration of hazardous material 1 at various time periods with 1.0 atmospheric pressure.

4. A sustainable shipbreaking approach for cleaner environment and better wellbeing

The shipbreaking methods currently exercised worldwide by the shipbreakers are not sustainable. No method is absolutely perfect to stop the contamination of soil, water and air in the shipbreaking yards and beyond. Hence, the IMO's safe and environmentally sound ship recycling guidelines emphasise on effective management of hazardous materials and wastes along with the minimisation of the risks in pollutions and contaminations during shipbreaking. However, no matter how much precautionary steps are taken, accidental spillage and contamination at yard ground during handling and management of hazardous materials cannot be ruled out. Even if shipbreaking is performed on a solid base, cleaning is done only after finishing entire breaking activities. Therefore, hazardous materials could be diluted in water if it rains during breaking activities and such contaminated water would be diffusing into the yard ground creating further contamination for the entire environment. Since shipbreaking yards are located near intertidal zones, any hazardous materials or wastes deposited on the yard ground could be washed away into the sea during high tides before being cleaned or transferred to designated storage area. Hence, it is important to perform the shipbreaking activities on a surface that can quarantine or trap any hazardous materials before being escaped to the environment. In order to achieve this goal, shipbreaking yards should be designed in a sustainable way through a minimal use of natural resources. Among the shipbreaking methods used, beaching method is considered as the worst in terms of the severity of environmental pollution. However, the use of this method might not be possible to ban or stop immediately due to a number of socio-economic factors. Until a suitable solution to these governing factors is discovered, an alternative shipbreaking approach that is sustainable, cheaper to invest, quicker to implement and comparatively effective to prevent environmental damages is urgently required. Therefore, such alternative approach could be to perform entire shipbreaking activities on a bed instead of a muddy surface. The bed (as can be seen in Figure 14) could be constructed in layers using gravels, pebbles and sands with various porosity and diffusivity characteristics.

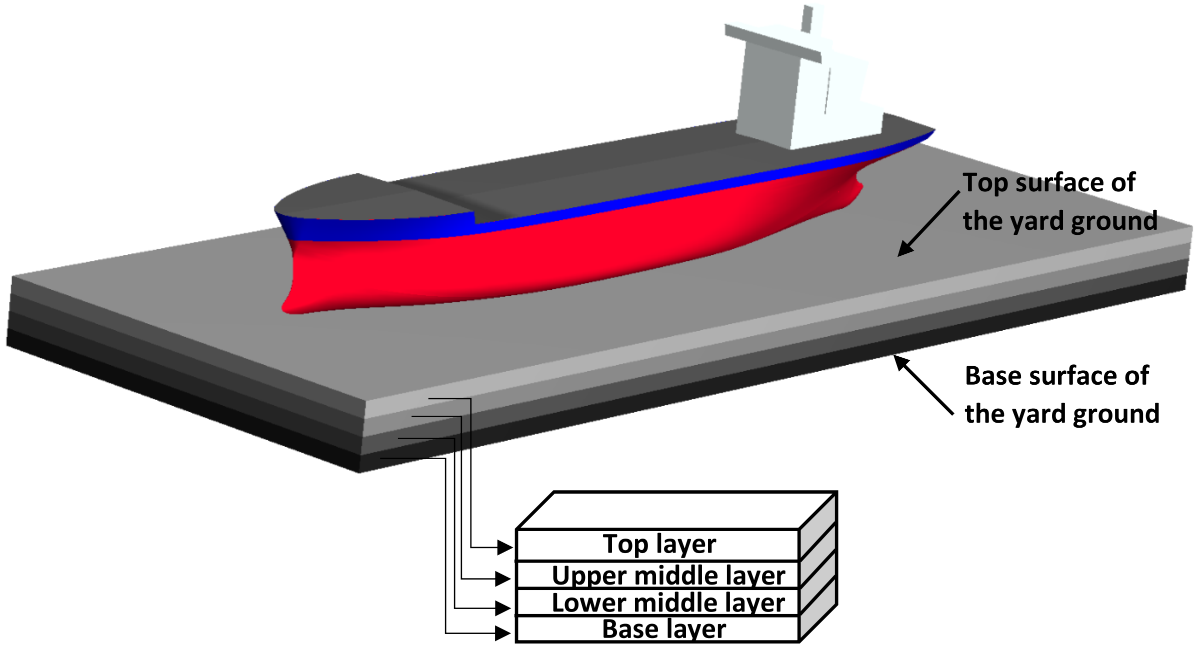

Figure 14: Schematic view of the proposed shipbreaking bed's configuration.

It is anticipated that the bed would be an effective way of trapping hazardous materials and wastes because each layer will have its own porosity and diffusivity characteristics. Thus, when hazardous materials deposit on the top surface of the bed and dilute with water, the hazardous materials or substances and its solution product would not be able to experience a smooth flow and surely there will be a pressure differential across the depth of the bed. Due to the obstructions to flow in various layers of the bed, the hazardous materials and its solution product would not be able to reach the base of the bed. As such, a shipbreaking yard's soil underneath the bed would not be contaminated. If further steps are taken to prevent the escape of hazardous materials and its solution product through the periphery of the bed, the environmental damage from shipbreaking activities could be minimised and/or eliminated completely. The approach would be sustainable as it is constructed mostly using natural resources i.e. pebbles, gravels, sands, soils etc. which are widely available, cheap and affordable. As the bed is not a permanent structure, whenever needed the materials used in the bed could be removed, rearranged, re-used or recycled with the ease of actions.

In order to verify the hypothesis explained above, further computer simulations have been performed using the methodology discussed before. The computer model of the bed is developed keeping the height same as is used in the previous simulations so that the effectiveness of the bed concept is directly compared with the traditional shipbreaking approach on muddy surface. The bed is further divided equally into four layers along the depth so that different materials can be used to construct each layer. In this study, ten different types of bed configurations have been considered as outlined in Table 4. The density and the porosity of the entire sand layer are considered as 510 kg/m^3 and 0.25 respectively. The porosity of individual particles of radius 5.0e-4 m has been taken as 0.34. The density of the mixture layer, which is a mixture of gravels, sand and tiny amount of a binder such as cement, is considered as 2400 kg/m^3. Besides, the density and the radius of the gravels within the mixture layer have been taken as 1750 kg/m^3 and 1.0e-2 m respectively. The layer constructed using pebbles has an overall density of 1423 kg/m^3. Each individual pebble within this layer has a density 2660 kg/m^3, radius 1.0e-2 m and porosity 0.5. All other parameters used in the simulations are the same as given in Table 3. The layers of Bed 10 constructed using pebble types 1, 2, 3 & 4 have the same properties as the pebble layers in other beds. However, the radiuses of pebble types 1, 2, 3 & 4 are considered as 5.0e-3 m, 1.0e-2 m, 1.5e-2 m and 2.0e-2 m respectively. The permeability in Bed 10 is considered as 1.88e-10 m^2 for the top layer, 1.38e-10 m^2 for the upper middle layer, 0.88e-10 m^2 for the lower middle layer and 0.38e-10 m^2 for the base layer.

Table 4: The bed configurations used in the computer simulation.

	Materials Used			
	Top layer	Upper middle layer	Lower middle layer	Base layer
Bed 1	Sand	Sand	Sand	Sand
Bed 2	Mixture	Sand	Sand	Sand
Bed 3	Mixture	Mixture	Sand	Sand

Bed 4	Mixture	Mixture	Mixture	Sand
Bed 5	Mixture	Mixture	Mixture	Mixture
Bed 6	Mixture	Mixture	Pebble	Sand
Bed 7	Mixture	Pebble	Pebble	Sand
Bed 8	Pebble	Pebble	Pebble	Sand
Bed 9	Pebble	Pebble	Pebble	Pebble
Bed 10	Pebble Type 1	Pebble Type 2	Pebble Type 3	Pebble Type 4

The results obtained from the computer simulations at one atmospheric pressure are depicted in Figures 15 and 16. It should be noted that the results presented in both figures are for non-reaction cases where hazardous material 1 do not react with hazardous material 2 when diluted in water (the dilution happens when water becomes available on the top surface of the bed due to rain pour or wave splash) and do not produce any solution products. Thus, each of the hazardous materials is simply transported through the layers within the bed.

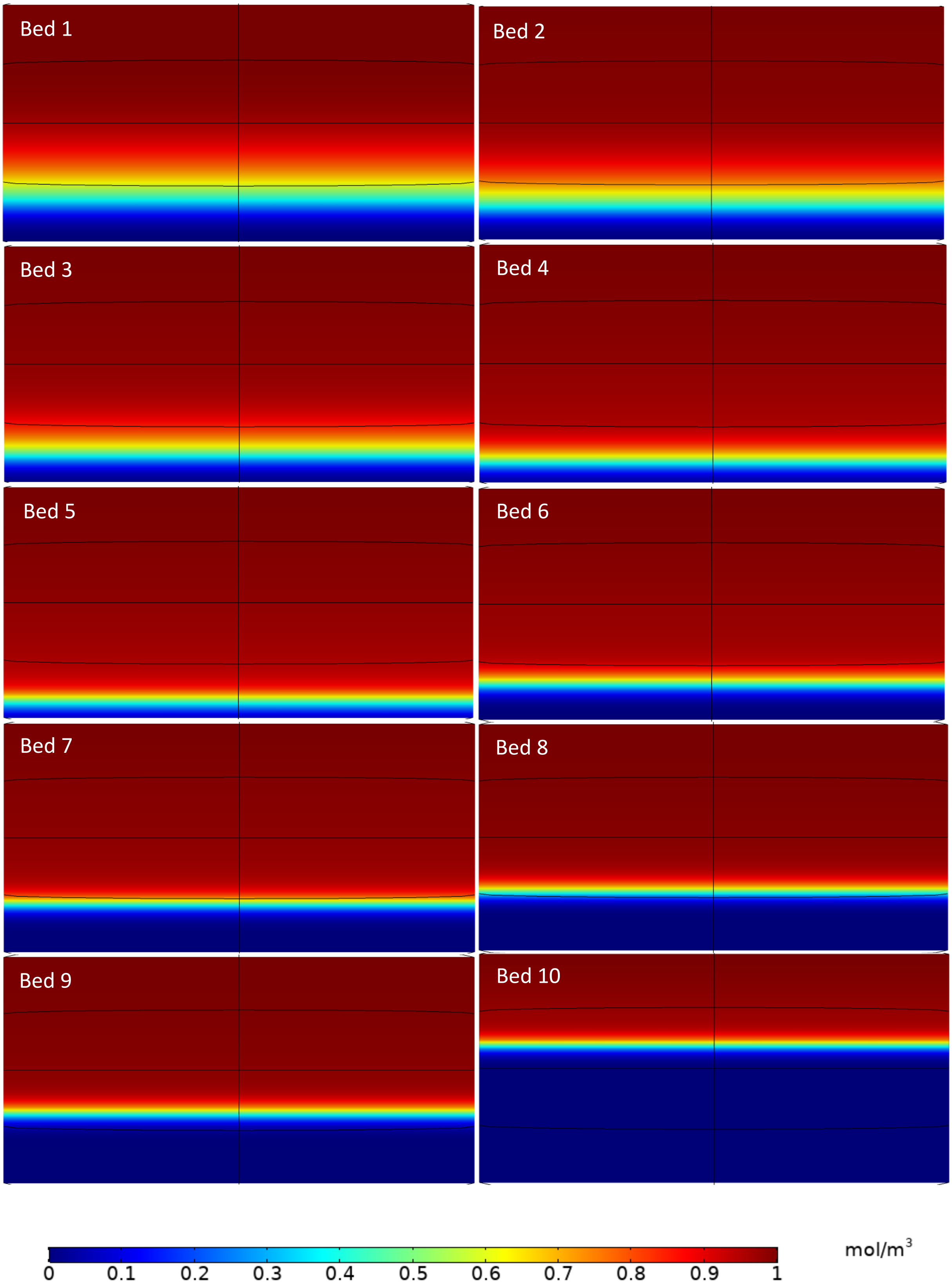

Figure 15: Variations in the concentration of hazardous material 1 across the depth of the bed.

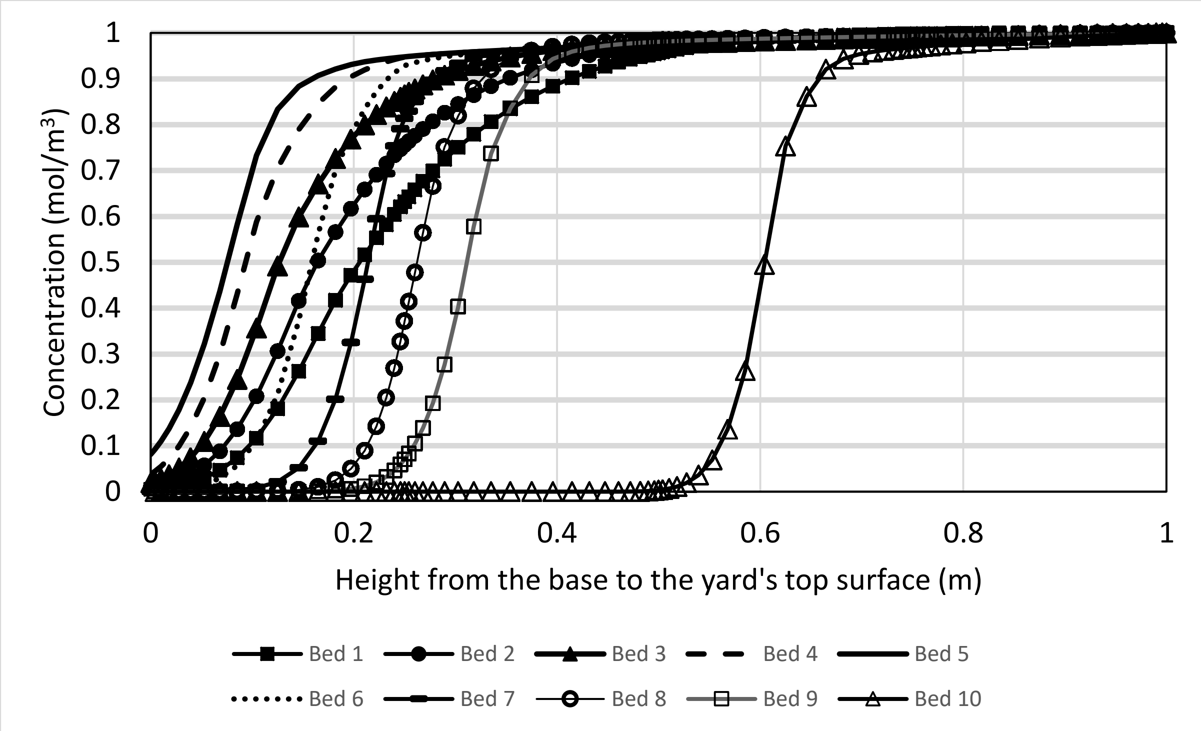

Figure 16: Variations in the concentration of hazardous material 1 from the base to the top surface of the bed.

Figure 15 shows the concentration gradients of hazardous material 1 at 50th second of the simulation. The red colour code indicates maximum concentration level (i.e. high contamination) and blue colour code indicates insignificant or zero concentration level (i.e. no contamination). This means that the larger the portions of the bed in blue colour, the better. It is evident that variations in bed configuration have significant impacts on the concentration of hazardous materials generated from shipbreaking activities. In Bed 1, the top layer and the upper middle layer both have been fully contaminated by the hazardous material, the lower middle layer and the top portion of the base layer have been contaminated partially. The concentration of the hazardous material reaches to its maximum quantity up to the middle of the lower middle layer for Bed 2, up to the bottom quarter of the lower middle layer for Bed 3, up to the top of the base layer for Bed 4 and up to the middle of the base layer for Bed 5. It is interesting to note that the hazardous material's concentration level reverses its trend for Bed 6 to Bed 10. The concentration levels are zero or close to zero for most portions of the base layer in Bed 7, entire base layer in Bed 8 as well as in Bed 9. Bed 10 is most effective in preventing contamination as the hazardous material could only reach up to the middle of the upper middle layer leaving zero concentrations in bottom two layers. This is because the permeability in Bed 10 decreases from the top layer towards the base layer and thus the pebbles in both the lower middle layer and the base layer resist the downward flow of the hazardous material. As a result, the hazardous material is trapped within the top two layers of the bed and cannot reach to the sand/soil underneath the bed. Therefore, the surrounding environment of a shipbreaking yard could be kept pollution free by performing the entire shipbreaking activities on a bed constructed in layers using pebbles of various diameters.

The amount of hazardous material 1 concentrated across the depth of the bed is plotted in Figure 16 at the 50th second of the simulation considering 1.0 atm pressure at the top surface of the bed. The figure reveals that the concentration amount at a depth of 80% measured from the top surface of the bed is 0.47 mol/m^3 in Bed 1, 0.62 mol/m^3 in Bed 2, 0.77 mol/m^3 in Bed 3, 0.90 mol/m^3 in Bed 4, 0.93 mol/m^3 in Bed 5, 0.78 mol/m^3 in Bed 6, 0.32 mol/m^3 in Bed 7, 0.05 mol/m^3 in Bed 8, 0.006 mol/m^3 in Bed 9 and 0.0 mol/m^3 in Bed 10. Therefore, the construction configuration of Bed 10 seems to be the most effective way to control the contamination of soil and surrounding environments of a shipbreaking yard. Bed 10 configuration includes pebbles of various sizes stacked in four layers. The pebbles in the top layer are of very small sizes whereas the base layer consists of pebbles with very big sizes. This type of configuration leads to develop a shipbreaking bed with variable permeability across the depth. As the size of the pebble in the top layer of the bed is very small, the diffusion of hazardous materials and its solution into the pebbles is negligible. Hence, the top layer of the bed, with high permeability and smaller sizes of pebbles, just let the hazardous material and its solution to pass through. Comparatively lower permeability in upper middle layer of the bed slows down the transportation of the hazardous material and its solution. This enhances the diffusion of hazardous material and its solution into the pebbles which are of comparatively bigger volume. This happens because the pebbles get sufficient time and space to absorb. Such diffusion process reduces the total concentration of hazardous materials into porous regions of the bed. Thus, the permeability of the bed, the size of the pebbles and the diffusion characteristics are important factors in defining the effectiveness of the proposed bed for minimising and/or eliminating soil contamination during shipbreaking activities.

5. Conclusions

Shipbreaking/ship recycling is considered as a very hazardous and dangerous activity as ship carries hazardous materials on board in the form of construction items and/or cargos. Hence, shipbreaking should be done in a confined environment following appropriate guidelines and regulations. Current shipbreaking methods and practices have created worldwide outcry. This is because current practices pose significant threats to human health and the environment. A number of shipbreaking methods are currently used by the shipbreaking yards but none of the methods is completely effective to control the spread of hazardous materials and hazardous wastes generated from shipbreaking activities. When compared, one shipbreaking method is slightly better than the other but the chances of water, air and soil contaminations cannot be ruled out for all available methods. With this in mind, a computer model of a portion of a shipbreaking yard ground has been built and analysed using a multiphysics commercial software package. Based on the input parameters supplied to the simulation, it only took 110 seconds for a hazardous material (that was initially deposited on the surface of the yard ground) to diffuse up to one meter depth of the yard ground. The shipbreaking/recycling guidelines produced by the appropriate authorities have emphasised on taking precautions for avoiding environmental damage. However, accidental spillage and contamination at yard ground during handling and management of hazardous materials cannot be avoided. It is extremely difficult (or impossible in some cases) to clean the yard ground and make it contamination free. Hence, this study has investigated an alternative approach to the current shipbreaking practices. A shipbreaking bed constructed in four layers using mixed materials (i.e. defined herein as 'mixture'), pebbles and sands with various porosity and diffusivity characteristics has been modelled and the concentrations of hazardous materials into the ground have been studied. It has been identified that if a shipbreaking bed is constructed using pebbles of various sizes in such a way that the pebble size gradually increases and the bed permeability gradually decreases across the depth starting from the top surface of the bed, the concentration of hazardous materials can be restricted. In other words, the chances of hazardous materials contaminating the surrounding environment can be minimised and/or completely eliminated. The proposed approach is considered sustainable as the bed is constructed mostly using natural resources i.e. pebbles, gravels, sands, soils etc. which are widely available, cheap and affordable. Whenever needed the materials from the bed could be removed, rearranged, re-used or recycled with the ease of actions. The proposed shipbreaking process would be a breakthrough in achieving cleaner productions of raw materials and would provide advanced guidelines to the shipbreaking industries for implementing immediately without incurring significant costs. It should be noted that the conclusion drawn here on the effectiveness of the bed approach is completely based on the parameters supplied to the computer simulations. The appropriateness and the accuracy of the values of the input parameters are the main governing factors to reach a definitive conclusion. However, investigation of the accuracy as well as the characteristics of the input parameters is out of scope of the current study. Therefore, further research and computer simulations are planned to obtain a firm conclusion once the accurate values of a number of key parameters are identified. The new results obtained from the computer simulations using updated input parameters are also planned to be verified through physical experiments conducted in real time environment and will be reported in future publications.

Author Contributions:

Md Jahir Rizvi: Conceptualization, methodology, formal analysis, investigation, writing, project administration. **Mohammad Rafiqul Islam:** Literature survey, data curation. **Olalekan Adekola:** Review and editing. **Oguguah Ngozi Margaret:** Literature survey, review and editing.

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Nomenclature:

CIS: The Commonwealth of Independent States
IMO: the International Maritime Organization
MEPC: Marine Environment Protection Committee
HCFC: Hydrochlorofluorocarbon
k^f : the rate factor for forward reactions
k^r : the rate factor for reverse reactions
$C_{HazMat1}$: the concentration of hazardous material 1
$C_{HazMat2}$: the concentration of hazardous material 2
$C_{HazMatS}$: the concentration of the solution product of the hazardous materials
N : the number of particles per unit volume
r : the non-dimensional radial coordinate from the centre to the surface of the particle
r_{pe} : the particle radius that can be changed without changing the geometry
ε_{pe} : the porosity of the particle
c_{pe} : the concentration of hazardous materials in the particle
D_{pe} : the diffusion coefficient of hazardous materials into the particle
R_{pe} : the reaction source term for the particle
ε : the porosity of the yard ground
ρ_{yard} : the density of the yard ground
ρ_{pe}: the density of the sand/soil particles
N_{inward} : the molar flux from the solution into each particle
h_D: the film mass transfer coefficient
c : the concentration of the hazardous materials in the solution